Station Path Corrections based on Event Cluster Analysis

Hans Israelsson, Joydeep Bhattacharyya, István Bondár, Keith McLaughlin, Xiaoping Yang

Group 2 Consortium Documentation, Phase-1 delivery

August, 2001

Summary

We summarize analysis of about 4,000 P phase station path corrections at regional distances estimated with JHD (Joint Hypocenter Determination) for 47 event clusters in Europe, Middle East and North Africa. Ninety five per cent of the estimated corrections, determined relative to the standard IASPEI91 travel time tables, were within +- 3.5 sec. The median of uncertainties of the estimated values was about 0.3 sec (90% confidence intervals). Large negative corrections (fast paths) occurred in the shield and platform areas of Northern and Eastern Europe while large positive corrections (slow paths) occurred predominately in the tectonic regions of the Mediterranean. Corrections with outlying values larger than 10 sec occurred mostly at distances around 15 degrees. Measurement and phase identification errors of arrivals could have contributed to the outlying values around this distance. The path corrections as a function of distance, both among cluster pairs and station pairs, show high correlations for distances up to 1 degree supporting the validity of the 1 degree sampling of SSSCs.

Path corrections based on the CUB 3D velocity model (CUB1.0) show encouraging correlations with the empirical JHD based corrections. Correlations for clusters in the Northern and Eastern part of Europe are generally high. Although correlation values are much lower for clusters to the south there is generally some correlation for paths longer than about 5 degrees. Velocity variations at shallow depth of the CUB1.0 model might have been smoothed out and that could explain the lower correlations for shorter distances. Such a smoothing effect of the CIB1.0 model in general might also explain that the ranges of the JHD corrections are clearly larger than those based on CUB1.0 for most clusters. The overall improvement in the fit to the empirical JHD corrections provided by the CUB1.0 model relative to the IASPEI91 model is demonstrated by the 30% reduction in the bulk standard deviation for all the data; the 1.53 sec standard deviation for the JHD corrections dropped to 1.1 sec for that of the CUB1.0-JHD differences. The *a priori* CUB1.0 model errors might be on the conservative side as their distance dependence was similar to the variation with distance of the standard deviation of the JHD path corrections.

INTRODUCTION

This document is part of the Phase 1 delivery by the Group 2 Location Calibration Consortium. We summarize results for empirical station path corrections obtained from event cluster analysis. The event cluster analysis serves as a validation tool of three areas of the location calibration: *(1)* Ground Truth (GT) events, *(2)* 3D velocity models by comparing empirical and model based corrections, and *(3)* model errors.

The empirical corrections analyzed here were estimated with Joint Hypocenter Determination (JHD) and were calculated relative the IASPEI91 standard travel time tables for first arrival P phases at distances between 2 and 20 degrees. The empirical corrections are also compared with corrections derived from a 3D velocity model by CUB (CUB1.0 model).

ESTIMATION OF EMPIRICAL CORRECTIONS

The JHD program by Dewey (1972, 1989) was used to estimate path corrections. The program was applied to event cluster data extracted from the ISC web site and the NEIS ftp site. The procedures used in the compilation of data and JHD estimation are described by Israelsson (2001a). The compilation of event clusters, which focused on the European part of the study area of the Group 2 Calibration Consortium, was driven by Reference Events of GT0-5 (Bondar et al., 2001). As part of the cluster analysis attempts were also made to define additional GT events from the resulting JHD solutions. The results of this effort to generate additional GT events are described by Israelsson (2001b) and Israelsson and Hofstetter (2001). Event clusters were also defined without available GT information in order to extend the geographical coverage in the Mediterranean region. Such additional clusters without GT were assigned a GT category of 25 km. The JHD processing was validated with a few clusters which included several GT0-1 events (Israelsson, 2001a) and with an independent cross-validation with the so called Hypocentroidal Decomposition (HDC) method, Israelsson et al. (2001).

The compilation and JHD processing resulted in 47 event clusters, 19 with GT0-5 and 28 with GT25. A number of potential compiled clusters had to be discarded in the course of

JHD processing due to an insufficient number of degrees of freedom of the data. Table 1 summarizes the characteristics of the event clusters that were analysed. The number of events in each cluster varies between 4 and 64 with a median of 19 events. The diameters of the clusters range between 5 and 55 km with a median of 30 km. As a result of the JHD the diameter of more than half of the clusters shrank and the scatter of the epicentres (tightness) was reduced for about 75% of the clusters. The total number of stations used for each cluster varied between 13 and 361 with a median of 142 stations. The corresponding numbers for regional stations range from 2 to 259 with a median of 93 stations.

The map in Figure 1 shows the geographical distribution of the clusters with indication of available GT data. Clusters with GT0-1 are all located in the northern part of the study area. The GT events for these events are mostly at zero depth (nuclear explosions at Azgir, Astrakhan, and Orenburg, Russia and chemical explosions at Lubin and Silesia, Poland). Almost half of the clusters are in Italy (10) and Greece (11).

During the JHD processing, depths of all events were held fixed at that of the GT event, so that in fact JED or Joint Epicenter Determination would be a more appropriate term than JHD. In the following we use the acronym JHD, however, to refer to the underlying program used in the estimation.

Measurement errors of arrival times were estimated from pair-wise station arrival differences independent of the JHD program (Israelsson, 2001c). Below, these errors are compared with the estimated path corrections and associated uncertainties.

JHD PATH CORRECTIONS

For all 47 clusters taken together station path corrections were estimated for 4345 paths with distances less than 20 degrees. The path corrections were distributed over 744 stations. The lower map in Figure 1 shows the coverage throughout the area of these path corrections. The coverage is dense across the Mediterranean region and more sparse in northern and eastern Europe.

Uncertainty in JHD path corrections

As a measure of uncertainty in the estimates of the JHD path corrections we use the 90% confidence intervals, which, in turn, are defined in a standard manner by the standard deviations of arrival time residuals, number of observations, and the Student t-distribution quantile. A robust estimate of standard deviations, the median absolute deviation scaled to normal consistency (also called "mad" estimate), are used in this report. About 4% of the estimated path corrections were omitted in the analysis below as they were based on less than 4 observations or had confidence intervals larger than 4.0 sec. The distribution of the confidence intervals (half width) is represented by the histogram in Figure 2; the median is 0.3 sec and 75% of the uncertainties are within 0.5 sec.

Figure 2 also shows the estimated confidence intervals as a function of epicentral distance (lower frame). As expected from the distance dependence of measurement errors, included in the plot for comparison (Israelsson, 2001c), the confidence intervals also increase with distance. The peak around 15 degrees for the confidence intervals is less pronounced than the peak for the standard deviation of the measurement errors; the peak is reduced due to the smoothing effect of the number of observations used for estimates of the uncertainties in path corrections.

Variation of JHD path corrections

Figure 3 shows the distribution of all JHD path corrections. The corrections were normalized for each cluster by subtracting the median of the path corrections for stations at distances between 30 and 90 degrees. If no teleseismic stations were available then no normalization was made. Most JHD path corrections are within 5 sec and within this range they approximate a Gaussian distribution quite well. There are also a few outlying observations with the largest being almost 15 sec (station WTS for the Rionero South cluster in Italy at 12.8 degrees based on 5 observations). The median of the corrections is slightly positive (0.6 sec), which means slower travel times than that of IASPEI91. The overall spread in the path corrections is characterized by a standard deviation of 1.53 sec. This is clearly a smaller scatter than one would expect from the model errors used for the

IASPEI91 tables. The normalization applied to the corrections described above can have narrowed the scatter as the JHD determination as a boundary condition set the average of corrections estimated to each cluster to zero.

Figure 4 shows the corrections as a function of distance. Apart from occasional outliers the corrections show similar ranges except for distances around 15 degrees where the range becomes larger. This effect is also illustrated in the lower diagram of Figure 4 where the standard deviation of the estimated JHD corrections is plotted as a function of distance (in 1 degree bins). The variation in standard deviation is similar to that of the standard deviation assumed for the CUB1.0 model errors (Shapiro, 2001).

The maps in Figure 5 demonstrate the variation by path of the JHD corrections. Paths with large negative (< -2 sec) (fast paths) and with large positive (> 2 sec) (slow paths) corrections separate clearly on the maps with fast paths concentrated in the northern shield/platform regions of the study area and slow paths in the southern tectonic regions. Note also the "fast" paths going from the southwestern Middle East to Greece.

Correlation between JHD path corrections

Event clusters located close to one another allow comparisons of consistency in the estimated path corrections. The centre of some clusters are within 30 km. Figure 6 compares the JHD path corrections of 4 pairs of clusters that are close which also show general agreement. The 4 pairs are located in widely separated regions of the study area. The small offset that can be noticed for the two Spanish event clusters can be attributed to uncertainty in the origin time of the events held fixed in the JHD and the normalization described above did not remove this effect. There is high agreement between corrections for the two Polish clusters in Lubin and Silesia in spite of a separation of more than 200 km. This is probably an indication of slowly varying lateral variations of the velocity for areas traversed by paths for these two clusters.

In Figure 7 (upper diagram) the correlation coefficient has been plotted for pair-wise comparisons of JHD path corrections as a function of the distance between the cluster centers with the same station. Only data for pairs with distances less than 5 degrees are

included in the figure. For separations less than 0.5 degree there is generally high correlation. And the correlation holds up out to about 1 degree for all pairs with the exception of one case. Beyond 1 degree the correlation starts to deteriorate, although for a fairly large number of cases the correlation is still high out to about 2 degrees.

A comparison of the correlation between JHD path corrections can also be made for station pairs. In the lower diagram of Figure 7 the correlation coefficient is plotted for station pairs as a function of station separation for the same cluster. As one would expect, the data show similar features as for the pair-wise cluster comparison. With the larger number of observations (correlation coefficients for about 1200 station pairs based on 10 or more common clusters) the distance dependence of the correlation is mapped down to just a few km for the station pairs.

The high correlations exhibited for the empirical path corrections both among clusters and among stations for distances less than 1 degree lend support to use of event clusters without GT information (GT25) and to a 1 degree sampling for SSSCs. The correlation distance for the empirical corrections suggest that a resolution of 2° or 4° for a velocity model might result in under-sampled SSSCs.

COMPARISON OF MODEL BASED AND EMPIRICAL CORRECTIONS

The JHD corrections are compared with SSSCs calculated from the CUB1.0 model. The comparison is limited to *first arrival P* between 2-18 degrees (in all 3890 paths). The CUB1.0 SSSCs (zero depth) were calculated for each cluster centered at the location of the event held fixed in the JHD location (zero elevation). Some differences have been noted in SSSCs as a function of shallow depth, so this simplification is bound to introduce some scatter in the data. Furthermore, the SSSC values used in the comparisons were extracted with limited accuracy without interpolation from a polar co-ordinate output format with distances to the nearest 25 km and azimuths to the nearest 3 degrees. Possible differences in ellipticity and elevation corrections were not accounted for in the comparison. These corrections for the paths analyzed were small,

however (ranges of -0.37 - 0.26 and -0.04 - 0.46 for ellipticity and elevations, respectively, for all paths).

Another limitation in the accuracy of the comparison is imposed by the uncertainty of the origin time of many of the events held fixed in the event clusters. As indicated above such origin times determine the level of the JHD path corrections - a shift in the origin time introduces a corresponding shift in the path corrections. Hence, strict comparisons can only be made in a relative sense for each cluster. In comparisons based on data of more than one cluster the corrections were normalized; each set of JHD corrections and SSSCs for a given cluster was normalized to a zero median value.

Table 2 lists some comparison statistics for each cluster including median length of paths in degrees, range and standard deviation of JHD and of CUB1.0 values, correlation coefficient, and the standard deviation of the differences CUB1.0-JHD.

Correlations

Examples of correlations between the JHD corrections and SSSCs are given in Figure 8 for Azgir, Lubin, Annecy, and Mascara, Algeria, which all show clear correlation between the two path corrections - empirical and model based. Confidence intervals for the JHD estimates are indicated, while the assumed errors in the CUB1.0 errors are omitted as they are very large by comparison (see Figure 4). The data in Figure 8 shows another feature typical of most clusters, the JHD corrections span a larger range than the corresponding CUB1.0 values (slope < 1 in Figure 8).

Figure 9 shows the JHD corrections plotted on top of the CUB1.0 SSSC map for the Azgir, Russia and Lubin, Poland, clusters. As the origin time for the Azgir explosion, held fixed in the JHD, has been announced (Sultanov et al., 1999), the data in the map for Azgir relate to absolute values.The high correlation between the two types of correction for the two clusters result in general overlap of the colors. Notice, however, the outlying JHD correction for the Lubin cluster at a station in Denmark showing in striking red (slow path) against the blue (fast) background. The positive JHD correction in this anomalous

case could be due to low velocity of shallow sediments locally at the station that would not be accounted for by the CUB1.0 model.

Figure 10 compares the JHD corrections and the CUB1.0 for all the clusters combined with a correlation coefficient of around 0.3, The data in Table 2 shows that there is a fair (>0.3) or high correlation for about half of the clusters (21 out of 43). Pearson's correlation test was applied to each cluster. The null hypothesis assumes that the two types of corrections come from un-correlated data while the alternative hypothesis assumes positive correlation. The p-values of the test are included in Table 2. The low p-values suggest correlation in most cases; only for 6 clusters is the p-value larger than 0.5. Some of the low correlation values appear to be an effect of the distance distribution of the paths which are dominated by paths lengths around 5 degrees. For shorter paths correlations appear lower as illustrated by the two diagrams in Figure 10, where the correlation coefficient is shown as a function of distance. The data were separated into two sets, one included only clusters for which the correlation was higher than 0.3 and the remaining clusters made up the other set. For both sets there is a clear change in the correlation coefficient with low values at distances less than about 5 degrees. The correlation values in Figure 11 suggest that apart from shorter distances the empirical JHD corrections and model CUB1.0 values show fairly consistent correlation. There are also exceptions from the distance effect. For example, the event cluster at Annecy, France, dominated by near stations, shows high correlation, even if the ranges of the JHD corrections are much larger than those of the CUB1.0 values (see Figure 9).

In Figure 12 the cluster correlation values are plotted as a function of geographic location. The upper frame shows the coefficients for all the data (21 of 43 clusters have correlation>0.3), while only data at distances larger than 6.5^o were included for the lower map (24 out of 41 clusters have correlation >0.3; two of the clusters in the upper map had insufficient number of paths $> 6.5^o$ to be included in the lower map). Those clusters for which there were only data at short distances and that high correlation values (like Annecy, France) were retained in the lower map. The lower map suggest a geographical

variation of the correlation (distance effect "removed"); all clusters with low correlations are in Greece, Italy and Northern Africa.

Agreement between JHD and CUB1.0 is highest for clusters in the northern Europe. These are also mostly of GT1 category and surface events; for four out of six clusters were at zero depth (Azgir, Astrakhan, Lubin and Silesia). It is unlikely that the GT category should affect the correlation as JHD corrections correlate up to 50 km or more. The depth, however, could be a contributing factor to lower correlations for the shallow earthquake clusters.

Standard Error of Differences

Standard deviations of the differences in CUB1.0 SSSC - JHD path corrections are listed in Table 2 for each cluster. The values range from 0.56 to 1.92 with a median of 1.1. Figure 13 shows the bulk distribution of all the differences in JHD-SSSC which is approximately Gaussian. The median for the bulk distribution is 1.15 is in agreement with the median among the clusters. This agreement supports the normalization used in the comparison of JHD and CUB1.0 residuals, as the median for the clusters is independent of the normalization while the median for the bulk is not independent.

The upper frame of Figure 14 shows the cluster standard deviations of the CUB1.0-JHD differences by location. As might be expected, clusters with high correlations also generally have low standard deviations.

The median of standard deviations of the CUB1.0-JHD differences can be compared with the value 1.53 is the standard deviation of JHD values (see Figure 3), which represents a measure of the fit of the IASPEI91 tables to empirical travel times. The reduction of this measure by CUB1.0 from about 1.53 to 1.1 suggests improvement in calculated travel times with the CUB1.0 model relative to empirically observed times. This corresponds to and overall variance reduction of 48%. It should be noted that this conclusion assumes that the normalization of the JHD corrections is unbiased and may be an overestimate as the median of the variance reduction of the individual clusters is about 20%.

Uncertainties in the CUB1.0 model

In the comparisons above we have not accounted for uncertainties in JHD and CUB1.0 estimates. The standard deviations of the CUB1.0 SSSCs determined by Shapiro (2001) (see also Figure 4) and the estimated uncertainties for the JHD corrections can be accounted for in the comparisons between the JHD corrections and SSSCs. The 90% confidence intervals overlap in more than 99% of the cases. Thus, accounting for uncertainties in both JHD path corrections and SSSCs results in good agreement between the two types of correction, although correlation values in many cases are low. Indeed, it appears that the CUB1.0 model errors may be on the conservative side as indicated above. If we use confidence intervals with the CUB1.0 distance dependent model errors that are reduced by a factor of two there is overlap in about 80% of the cases, a degree of overlap one would expect for two independent 90% confidence intervals. The lower diagram of Figure 14 shows the standard deviation of the differences CUB1.0-JHD as a function of distance and the CUB1.0 model error curve is again included for comparison. Apart from distances around 15 degrees the CUB1.0 error is higher than the standard deviation of the differences.

CONCLUDING REMARKS

In summing up the event cluster analysis we give some bulk statistics from the results and suggest some issues to consider for future work.

JHD path corrections were calculated for more than 4,000 regional paths in Europe. The sampling of these paths across the study area is uneven with a heavy coverage of the Mediterranean. The uneven sampling should be kept in mind when interpreting bulk values. As a first step, however, such numbers serve as a useful baseline against which results of a more regionalized approach in analysis can be gauged.

About 95% of the empirical corrections are within +- 3.5 s of the IASPEI91 model. There were also outlying values up to almost 15 sec. Outlying values occurred predominantly at distances around 15 degrees, but were present also at distances throughout the regional range.

The estimated uncertainties of JHD corrections were less than 0.5 s (90% confidence interval) for about 75% of the corrections.

Calculated correlations of JHD corrections among clusters and stations as a function of distance suggest that cluster diameters up to above 50 km should be possible without being seriously affected by local velocity inhomogeneties.

The comparison with the CUB1.0 model showed high correlation for a few of the clusters. For only 6 clusters could the hypothesis of correlation in the data be rejected at a probability of 0.5 or more. It appears that correlation is fair for paths longer than about 5 degrees and that corrections with paths shorter than 5 degrees, in general, have reduced correlation. The bulk standard error between JHD-CUB1.0 differences was about 1.1 sec which is clearly reduced compared with the bulk standard error of the JHD corrections of 1.53 sec, which relates to the IASPEI91 model. This corresponds to a 48% variance reduction. This conclusion assumes that the normalization of the JHD corrections is unbiased. Some of the weak correlation between JHD and CUB1.0 values might be due to the approximations made in the comparisons and future work should attempt to refine calculations.

Generally the JHD corrections seem to span a larger range than the CUB1.0 corrections, which is likely an effect of smoothing of the CUB1.0 model (2 by 2° model). This raises the issue whether empirical corrections can be combined with model estimates to improve model based SSSCs locally. The estimated uncertainties of the CUB1.0 model also appears large compared with the scatter in the JHD corrections.

Many of the clusters were not constrained by GT information which contribute to scatter in the estimated corrections. Future work should aim at gathering GT information in such regions as Greece, Italy, and Turkey with their abundance of event clusters. Although such regions may not be of the highest priority for monitoring the readily available data provide a useful basis for studying issues of methodology in event cluster analysis. Effects of focal depth is another issue that should be addressed in future event cluster analysis and comparisons with model based path corrections.

REFERENCES

Bondar, I., Yang, X., Engdahl, B., Bergman, E., Israelsson, H., Hofstetter, A., Gupta, I., Wagner, R., Antolik, M. and K. McLaughlin, (2001), Group-2 Consortium Reference Event List, Group-2 Consortium Documentation, Phase-1 Delivery July17, 2001.

Dewey, J. (1972), Seismicity and tectonics in western Venezuela, BSSA, 62: 1711-1751.

Dewey, J. W. (1989), JHD89 and SE89 - Algorithms for Joint Hypocenter Determination and modified Single-Event Determination (Memo USGS).

Israelsson, H. (2001a), JHD Processing of Event Clusters, CMR Memo, April 12, 2001

Israelsson, H. (2001b), Note from JHD analysis of some event clusters in Europe, CMR Memo, April 20, 2001

Israelsson, H., (2001c), Measurement Errors from Event Clusters, CMR Memo, June 13, 2001

Israelsson, H. and R. Hofstetter (2001), JHD Analysis of Aqaba sub-cluster with regional stations, CMR Memo, April 26, 2001

Israelsson, H., Engdahl, B. and E. Bergman (2001), Cross validation of Two methods for Event Cluster Analysis, CMR Memo, Feb. 23, 2001

Shapiro, N. (2001), Model Error computed from variogram based on EHB data and CU model, (document in preparation).

Sultanov, D. D.; Murphy, J. R.; Rubenstein, K. D. (1999), A Seismic Source Summary for Soviet Peaceful Nuclear Explosions, BSSA 89: 640 - 647.

Table 1: EVENT CLUSTERS

Cluster	Epicenter	GT	No Event	No Sta	Geometry	
			Fix/Free[1]	<20/>20[2]	Daim[3]	Var[4]
Algeria, Blida	36.68 2.49	25	1/24	117/19	37.5/25.1	5.5/4.5
Algeria, Bordjbou	36.60 4.77	25	1/4	93/16	22.1/17.2	6.9/4.6
Algeria, El Asnam	36.31 1.59	25	1/59	172/185	55.7/53.0	5.9/5.6
Algeria, Mascara	35.52 -0.11	25	1/19	51/0	32.1/36.7	5.6/5.0
Aqaba Central	28.81 34.65	5	1/11	89/132	34.1/31.7	4.8/4.9
Aqaba North	29.19 34.72	5	1/13	56/102	42.5/53.2	7.6/7.2
Aqaba South	28.48 34.76	5	1/15	91/142	37.3/41.9	5.5/7.4
France, Annecy	45.94 6.09	1	1/11	73/0	11.2/11.3	2.1/2.6
Georgia, Racha East	42.44 44.00	5	1/23	48/177	48.3/38.4	7.9/5.3
Georgia, Racha West	42.58 43.25	5	1/24	28/123	38.1/38.7	5.4/5.2
Greece, Alani	40.11 21.62	25	1/19	42/2	35.7/33.4	6.8/5.6
Greece, Amfissa	38.30 22.45	25	1/20	140/48	30.1/32.6	5.5/5.3
Greece, Crete	34.95 23.05	25	1/28	139/108	34.6/31.4	5.2/4.9
Greece, Ionian Sea	35.97 21.95	25	1/17	139/69	45.9/43.2	8.5/8.5
Greece, Kanallkion	39.27 20.55	25	1/17	196/52	21.2/32.3	3.7/5.7
Greece, Kefallnia	38.07 20.25	25	1/12	163/104	19.2/38.5	2.9/6.9
Greece, Pagasae	39.26 22.81	25	1/19	148/101	17.6/18.8	3.3/3.0
Greece, Thermum	38.52 21.67	25	1/25	147/56	25.0/26.1	4.0/4.1
Greece, Thivai	38.24 23.26	25	1/30	139/89	19.7/21.4	2.8/3.0
Greece, Zakynthos	37.63 20.94	25	1/18	147/37	24.2/22.1	3.5/3.3
Greece, Zmfissa	42.04 19.05	25	1/22	127/7	22.2/26.0	3.6/4.5
Italy, Abruzzo	41.76 13.90	25	1/25	140/36	21.5/18.4	3.3/2.6
Italy, Forli	44.24 12.21	25	1/22	94/0	26.8/29.3	5.6/5.3
Italy, Gemona	46.30 13.19	25	1/32	178/104	25.4/29.1	3.5/4.5
Italy, Reggio	44.69 10.32	25	1/18	102/1	39.4/38.1	5.6/5.8
Italy, Rionero Central	40.78 15.77	25	1/25	157/32	36.8/36.2	5.9/5.6
Italy, Rionero North	40.91 15.37	25	1/29	102/40	26.3/29.3	3.9/3.8
Italy, Rionero South	40.65 15.40	25	1/18	93/31	26.2/26.3	4.1/3.7
Italy, Taormina	37.90 15.06	25	1/18	79/7	35.1/29.4	5.7/4.9
Italy, Umbria-Marche	43.01 12.80	5	1/64	259/102	47.7/45.2	6.4/6.2
Italy, Ustica	38.44 12.78	25	1/19	114/32	32.0/26.2	5.5/4.1

Table 1: EVENT CLUSTERS

Cluster	Epicenter	GT	No Event Fix/Free[1]	No Sta <20/>20[2]	Geometry Daim[3]	Geometry Var[4]
Montenegro, Kotai	42.29 18.68	25	1/14	84/5	20.8/24.2	3.4/3.0
Morocco, Alhoceima	35.19 -4.04	5	2/21	61/8	23.4/18.0	3.5/2.1
Morocco, Melilla	35.35 -2.50	25	1/21	56/5	29.2/25.5	4.4/3.5
Poland, Lubin	51.49 16.09	1	9/37	131/9	36.6/15.6	4.7/2.1
Poland, Silesia	50.35 18.82	1	1/23	31/1	24.4/23.9	3.8/3.8
Russia, Astrakhan	46.76 48.27	1	1/14	27/156	24.1/20.9	5.0/4.9
Russia, Azgir	47.90 48.16	1	1/7	27/167	14.3/8.7	4.0/1.6
Russia, Orenburg	51.36 53.31	1	1/5	12/135	5.5/4.2	1.1/0.7
Slovenia, Krm Mountains	46.31 13.63	1	1/21	115/0	18.2/12.1	2.5/2.3
Spain, Jayena	36.96 -3.78	5	1/18	59/2	43.1/37.6	4.7/4.1
Spain, Loja	37.21 -4.20	5	4/29	38/0	31.3/15.7	4.4/1.9
Spain, Murcia	38.12 -1.48	5	2/7	23/0	29.8/34.2	6.2/5.0
Switzerland, Engelberg	46.72 8.42	0	1/7	13/0	31.0/31.2	8.4/6.6
Turkey, Adana	36.88 35.50	5	2/14	65/42	41.3/52.7	6.8/9.6
Yemen, Gulf of Aden North	14.05 51.65	25	1/11	2/92	49.6/44.9	8.3/7.9
Yemen, Gulf of Aden South	13.09 50.96	25	1/14	2/102	56.5/46.2	10.0/6.2

1. Number of events held fixed and free in the JHD

2. Number of stations with distances less than and greater than 20 degrees

3. Diameter of event cluster before and after JHD (km)

4. Scatter in event locations from center of cluster before and after JHD (km)

Table 2: SUMMARY OF STATISTICS FOR JHD AND CUB1.0 CORRECTIONS

Cluster	No. Obs	Median path (º)	Range		Standard Deviation (sec)			Correlation	
			JHD	CUB1.0	JHD	CUB1.0	JHD-CUB1.0f	coeff.	p-value[1]
Algeria, Blida	108	8.4	-2.19 2.75	-2.00 1.16	0.86	0.44	0.92	0.32	0.00
Algeria, Bordjbou	78	8.1	-2.95 2.54	-1.38 1.03	1.11	0.50	1.05	-0.10	0.82
Algeria, El Asnam	136	10.9	-2.70 7.53	-2.51 1.01	1.34	0.87	1.45	0.09	0.16
Algeria, Mascara	51	6.4	-1.97 2.60	-2.11 1.82	0.89	0.79	0.80	0.57	0.00
Aqaba Central	57	4.3	-1.90 3.21	-1.88 1.22	0.61	0.44	0.70	0.07	0.30
Aqaba North	42	4.0	-2.09 7.52	-1.59 1.16	0.96	0.33	0.82	-0.06	0.68
Aqaba South	61	4.2	-1.39 5.37	-1.91 1.12	0.86	0.44	0.93	0.00	0.54
France, Annecy	58	2.2	-1.59 3.18	-0.97 0.90	1.45	0.53	1.05	0.67	0.00
Georgia, Racha East	38	13.5	-7.10 2.54	-4.74 2.09	1.92	1.04	1.35	0.75	0.00
Georgia, Racha West	20	13.2	-3.86 6.18	-4.06 2.76	1.96	1.87	1.16	0.37	0.05
Greece, Alani	40	3.0	-1.47 2.47	-0.76 0.46	1.23	0.24	1.19	0.11	0.25
Greece, Amfissa	105	4.9	-2.48 5.65	-1.56 0.85	1.38	0.44	1.48	-0.02	0.64
Greece, Crete	116	7.8	-3.61 7.38	-1.71 0.94	1.63	0.69	1.39	0.19	0.02
Greece, Ionian Sea	125	6.8	-3.13 8.27	-1.52 1.24	1.30	0.67	0.90	0.39	0.00
Greece, Kanallkion	183	6.5	-4.37 10.42	-2.81 1.27	1.38	0.50	1.19	0.44	0.00
Greece, Kefallnia	147	8.2	-5.08 5.50	-2.57 0.96	1.50	0.58	1.17	0.52	0.00
Greece, Pagasae	128	7.8	-3.11 4.88	-1.94 1.80	1.43	0.61	1.27	0.33	0.00
Greece, Thermum	130	5.4	-2.75 5.33	-2.19 1.20	1.86	0.56	1.62	0.03	0.38
Greece, Thivai	124	8.0	-3.21 7.36	-1.50 1.62	1.78	0.83	1.92	0.08	0.19

Table 2: SUMMARY OF STATISTICS FOR JHD AND CUB1.0 CORRECTIONS

Cluster	No. Obs	Median path (º)	Range		Standard Deviation (sec)			Correlation	
			JHD	CUB1.0	JHD	CUB1.0	JHD-CUB1.0f	coeff.	p-value[1]
Greece, Zakynthos	135	5.1	-3.91 8.64	-1.91 1.42	1.23	0.44	0.99	0.07	0.22
Greece, Zmfissa	118	5.9	-3.19 4.10	-3.21 0.89	1.37	0.42	1.24	0.39	0.00
Italy, Abruzzo	129	7.1	-2.10 3.61	-0.87 0.69	1.08	0.46	0.98	0.22	0.01
Italy, Forli	89	3.5	-2.29 2.19	-0.80 0.61	0.70	0.30	0.80	0.03	0.38
Italy, Gemona	168	6.0	-2.35 6.42	-3.89 1.53	0.85	0.73	1.16	0.03	0.36
Italy, Reggio	102	2.9	-1.67 2.13	-1.05 1.06	0.83	0.65	0.80	0.35	0.00
Italy, Rionero Central	151	6.1	-4.36 7.38	-2.18 0.81	0.98	0.42	1.11	0.34	0.00
Italy, Rionero North	95	7.0	-3.31 3.15	-0.87 0.83	1.10	0.44	1.13	0.01	0.47
Italy, Rionero South	87	7.4	-3.58 14.48	-2.09 0.71	1.20	0.56	1.33	-0.01	0.59
Italy, Taormina	65	5.9	-3.01 3.52	-0.80 0.69	1.53	0.24	1.38	0.06	0.30
Italy, Umbria-Marche	248	6.1	-3.28 3.26	-1.85 1.01	1.18	0.39	1.18	0.23	0.00
Italy, Ustica	109	7.6	-2.88 6.09	-0.78 1.47	1.85	0.31	1.84	0.36	0.00
Montenegro, Kotai	77	6.7	-3.04 3.20	-3.06 1.09	0.99	0.64	1.11	0.38	0.00
Morroco, Alhoceima	55	3.4	-1.55 2.37	-1.53 0.69	0.85	0.43	0.89	0.11	0.21
Morroco, Melilla	53	5.5	-1.92 2.13	-1.35 1.32	0.95	0.37	0.89	0.25	0.04
Poland, Lubin	127	6.4	-5.80 3.67	-3.93 1.01	1.22	0.74	0.95	0.74	0.00
Poland, Silesia	27	5.0	-5.28 1.80	-4.34 1.31	1.35	1.32	0.64	0.80	0.00
Russia, Astrakhan	19	16.1	-2.37 7.36	-1.46 2.15	1.44	0.89	1.57	0.38	0.05
Russia, Azgir	16	15.0	-2.45 3.64	-2.52 2.37	2.44	1.60	0.87	0.87	0.00
Slovenia, Krm Mountains	104	4.2	-1.73 2.19	-0.94 0.89	0.99	0.56	1.10	-0.06	0.76

Table 2: SUMMARY OF STATISTICS FOR JHD AND CUB1.0 CORRECTIONS

Cluster	No. Obs	Median path (º)	Range		Standard Deviation (sec)			Correlation	
			JHD	CUB1.0	JHD	CUB1.0	JHD-CUB1.0f	coeff.	p-value[1]
Spain, Jayena	58	5.9	-1.97 3.37	-1.34 1.58	0.70	0.87	0.86	0.32	0.01
Spain, Loja	31	3.4	-1.30 3.20	-0.89 1.56	0.82	0.67	0.83	0.32	0.04
Spain, Murcia	22	3.1	-1.52 2.08	-0.66 0.98	0.59	0.46	0.82	0.33	0.07
Turkey, Adana	54	5.2	-3.63 3.23	-0.85 1.02	1.05	0.24	0.58	0.19	0.08

1. p-value from Pearson's correlation test.

JHD Event Clusters

4231JHD Paths with Distance < 20 degrees
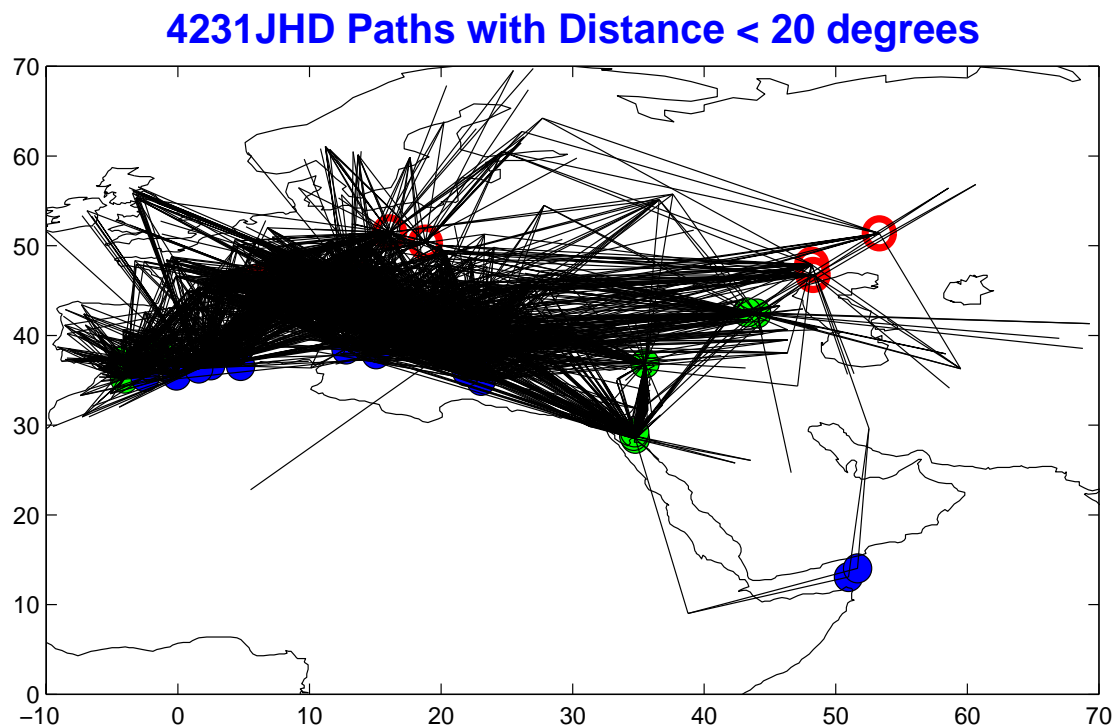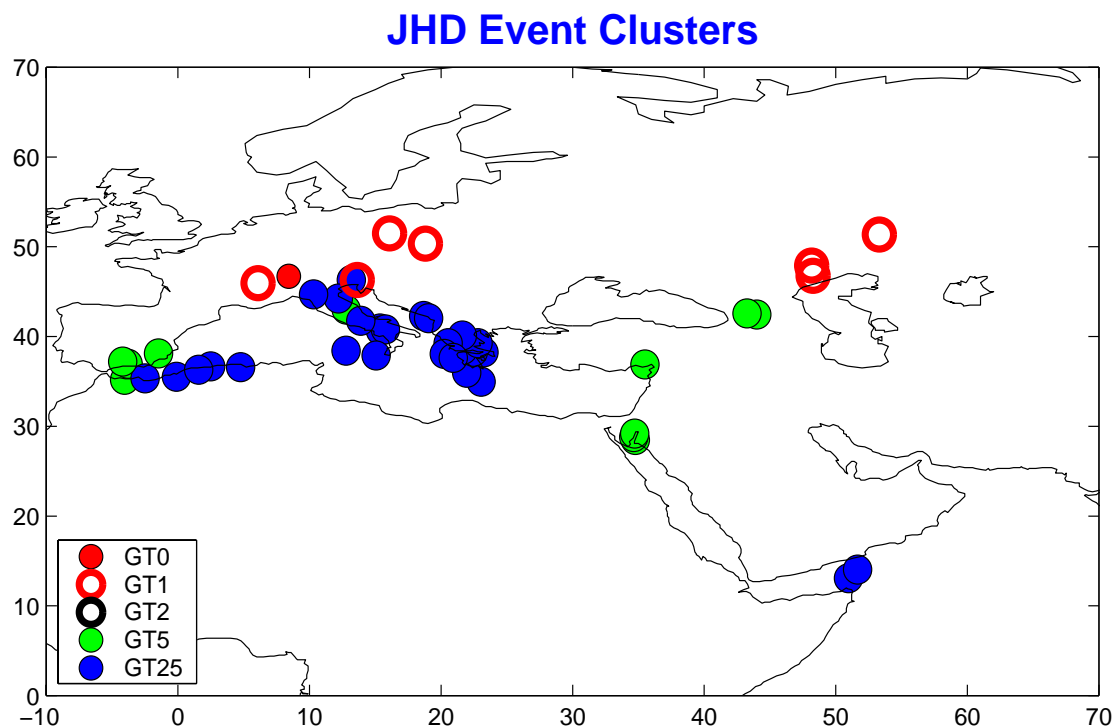
Figure 1. Geographical distribution of event clusters (top) and station path coverage (bottom)

Histogram of Confidence Interval of JHD path cor
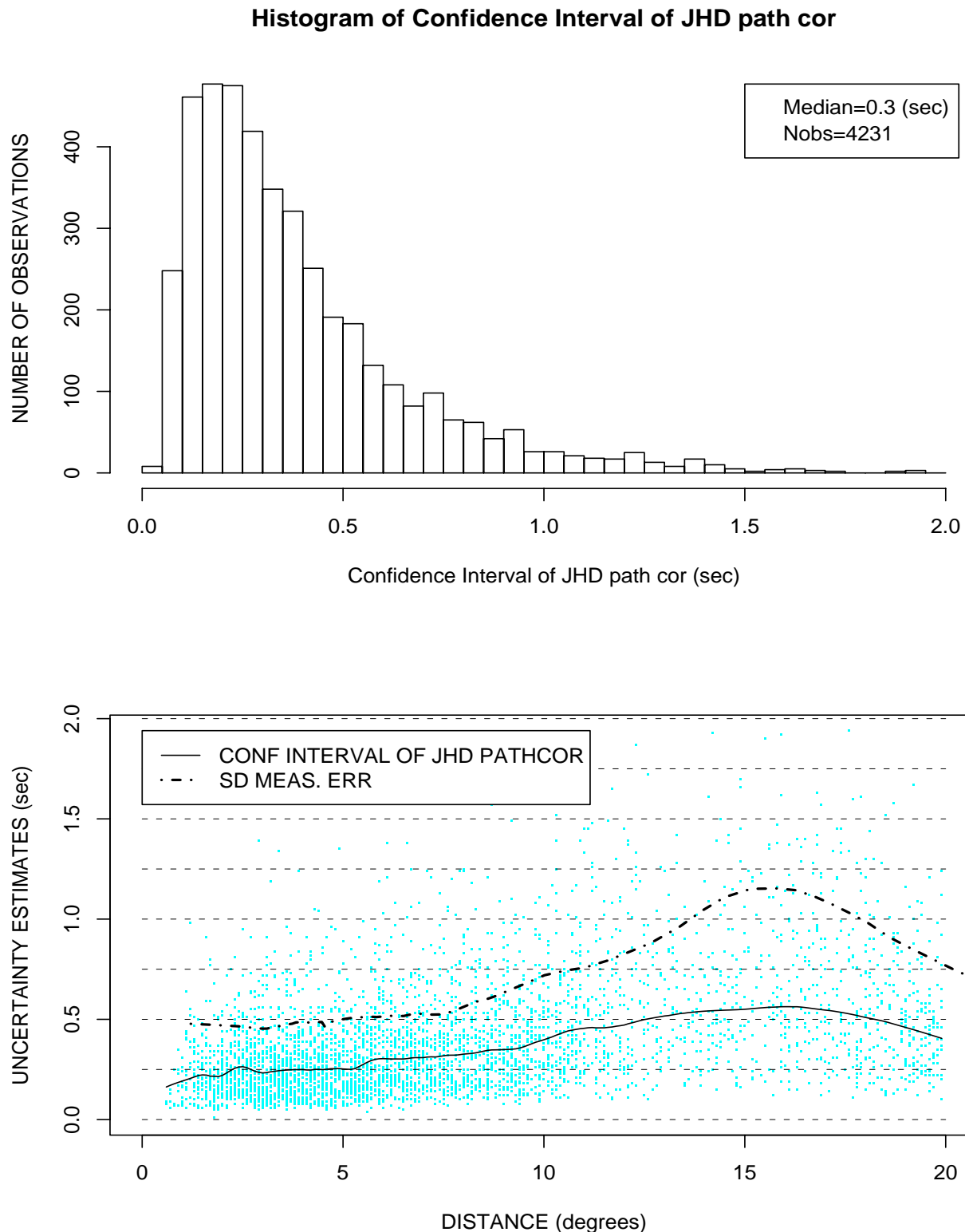
Figure 2. Histogram (top) of confidence intervals (90% half width) for estimated JHD corrections. In the lower frame confidence intervals (90% half width) of estimated JHD corrections are plotted as a function of the path length (degrees). The full line is a robust locally weighted regression line. The dashed line is the distance dependence of measurement errors estimated by Israelsson (2001c). The peak around 15 degrees of the confidence interval is probably caused by measurement and phase identification errors.

Histogram of JHD Path corrections

Nobs=4231
Median=0.68 (sec)
Mad=1.53 (sec)

JHD Path corrections (sec)

Normal Q–Q–plot of JHD Path corrections

90% 95%   99%

Theoretical Quantiles
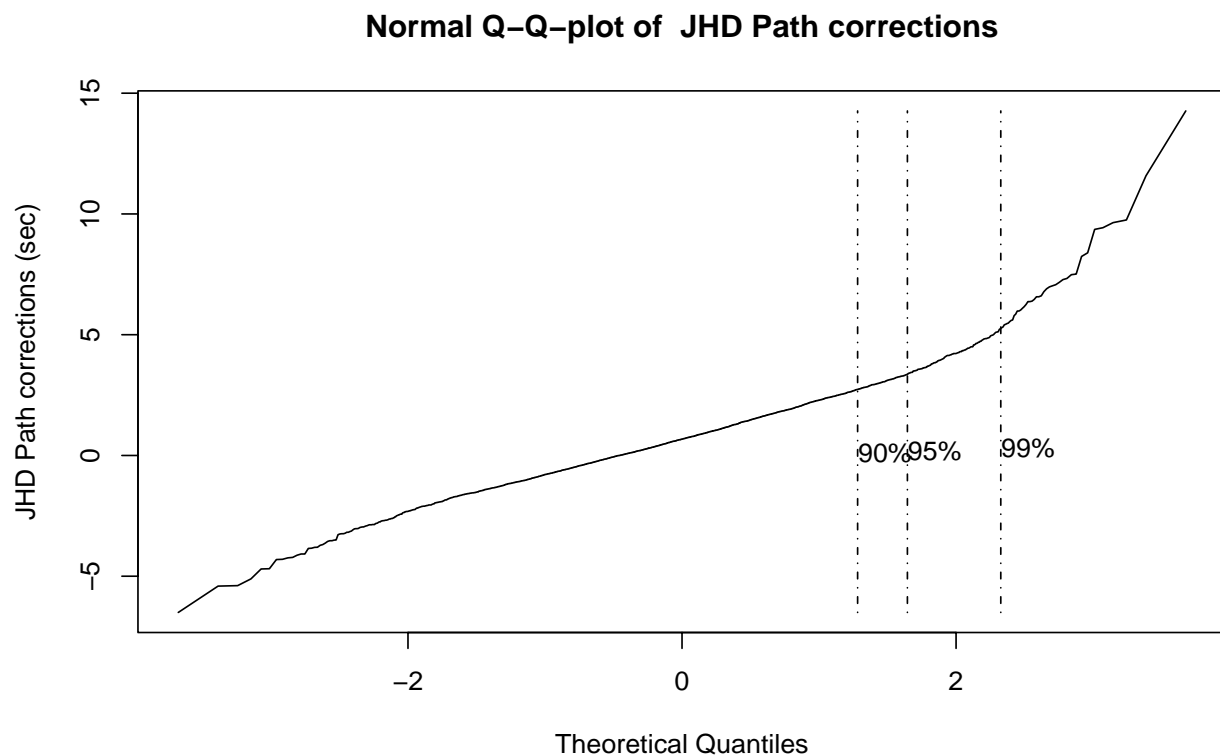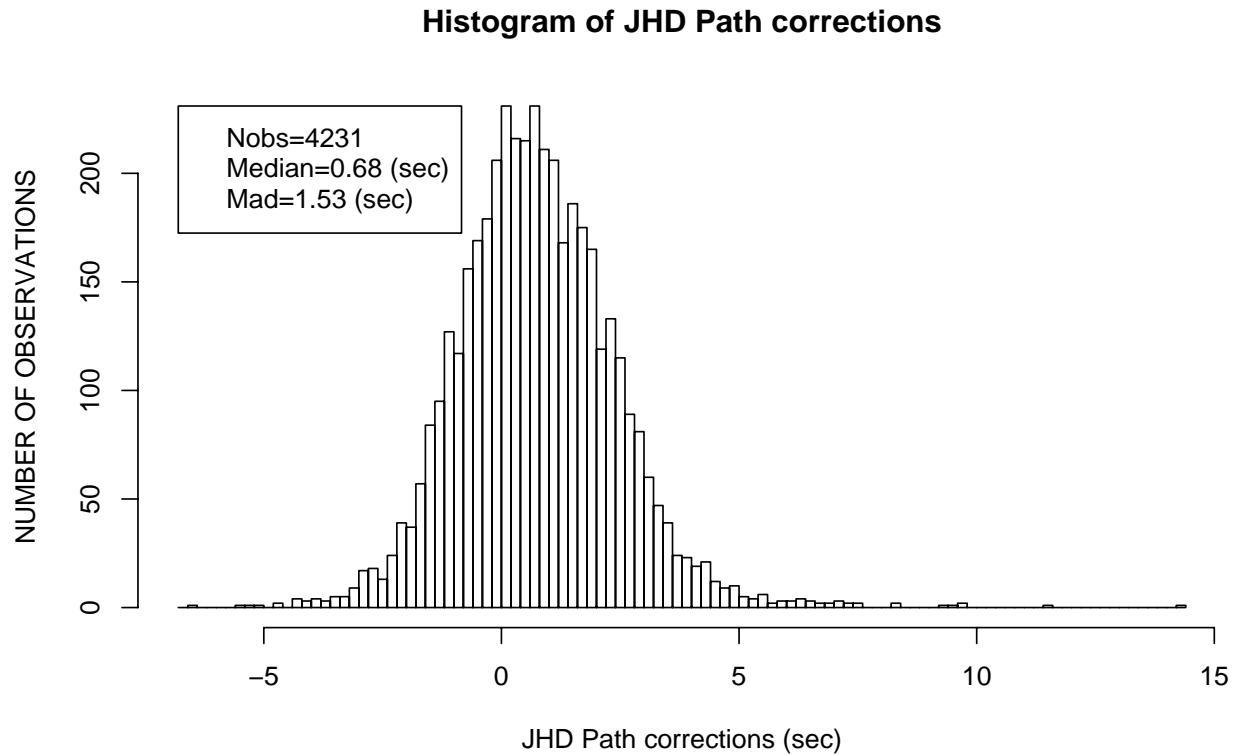
Figure 3. Histogram of all JHD path correction illustrating their spread (top) and normal Q-Q plot (bottom) showing that the distribution is only approximately Gaussian. The scaling of the Q-Q plot makes empirical cumulative distributions that are Gaussian follow a straight line.
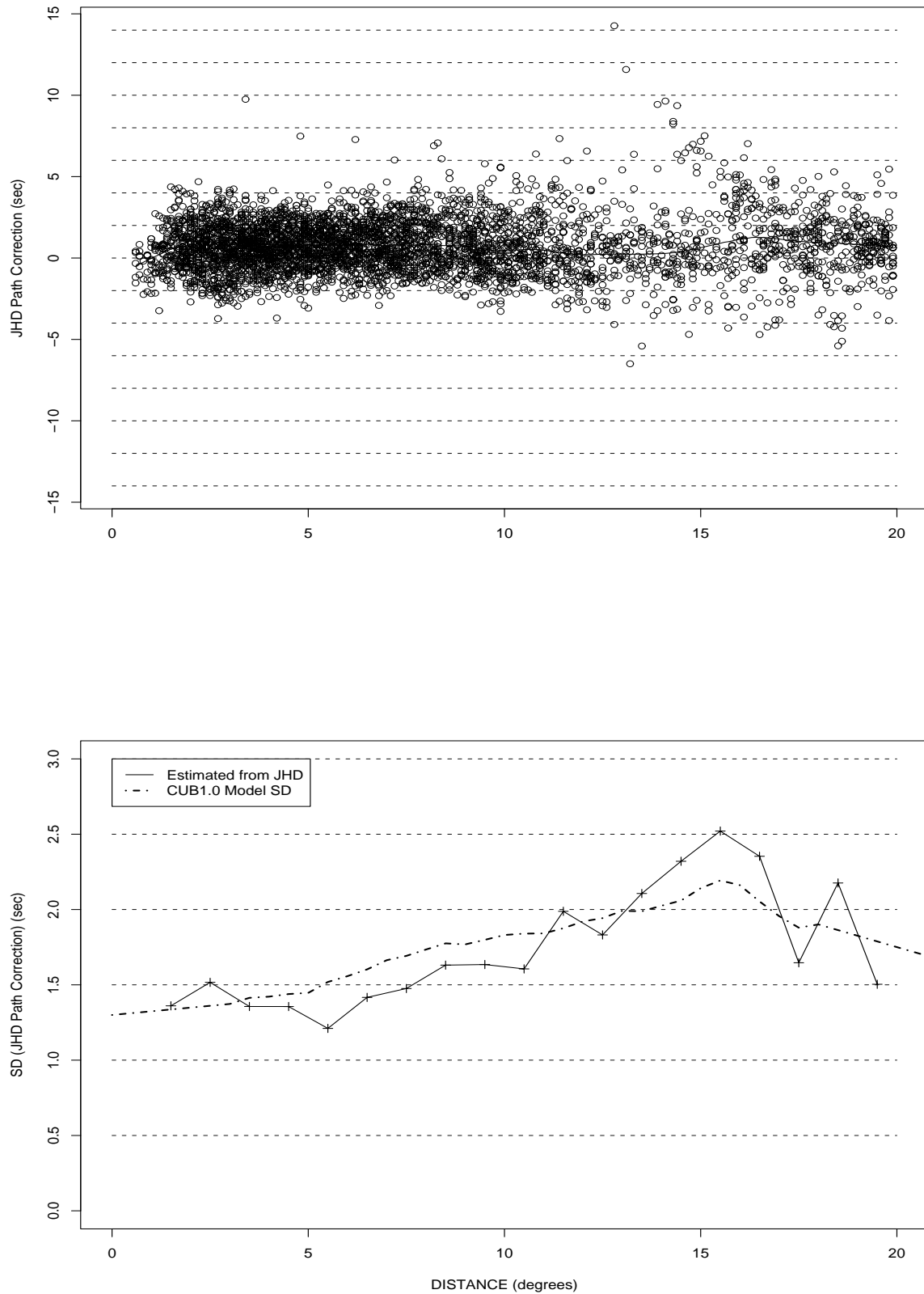
Figure 4. JHD path corrections as a function of distance (upper) and the standard deviation of the path corrections as a function of distance (lower). The distance dependent a priori model error of the CUB1.0 model is drawn in the lower diagram for comparison.

147 paths with −25 <= JHD pathcor < −2

859 paths with 2 <= JHD pathcor < 25
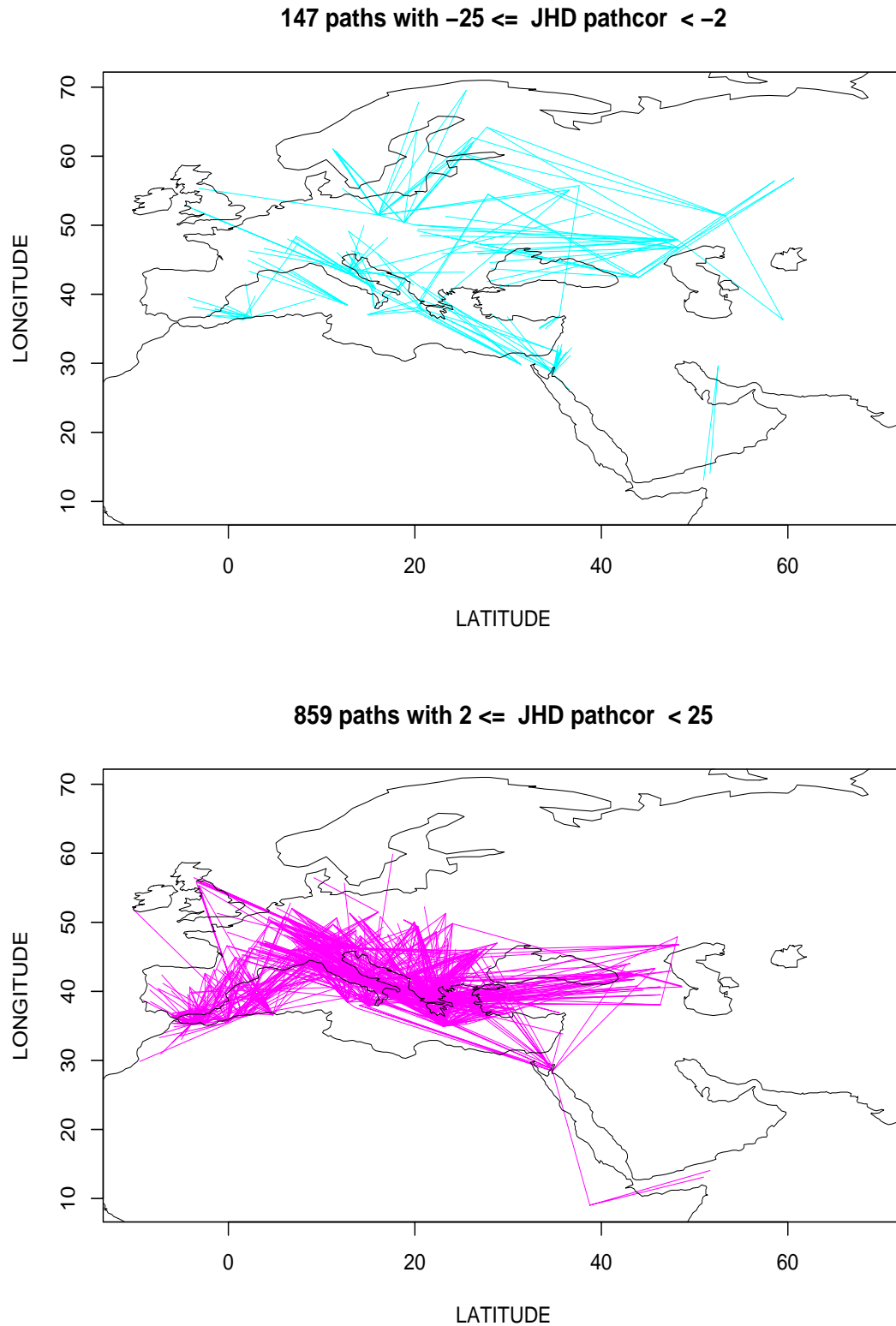
Figure 5. Paths with large negative (upper map) and positive (lower amp) residuals plotted separately. Fast paths (negative) occur mostly in northern and eastern Europe.
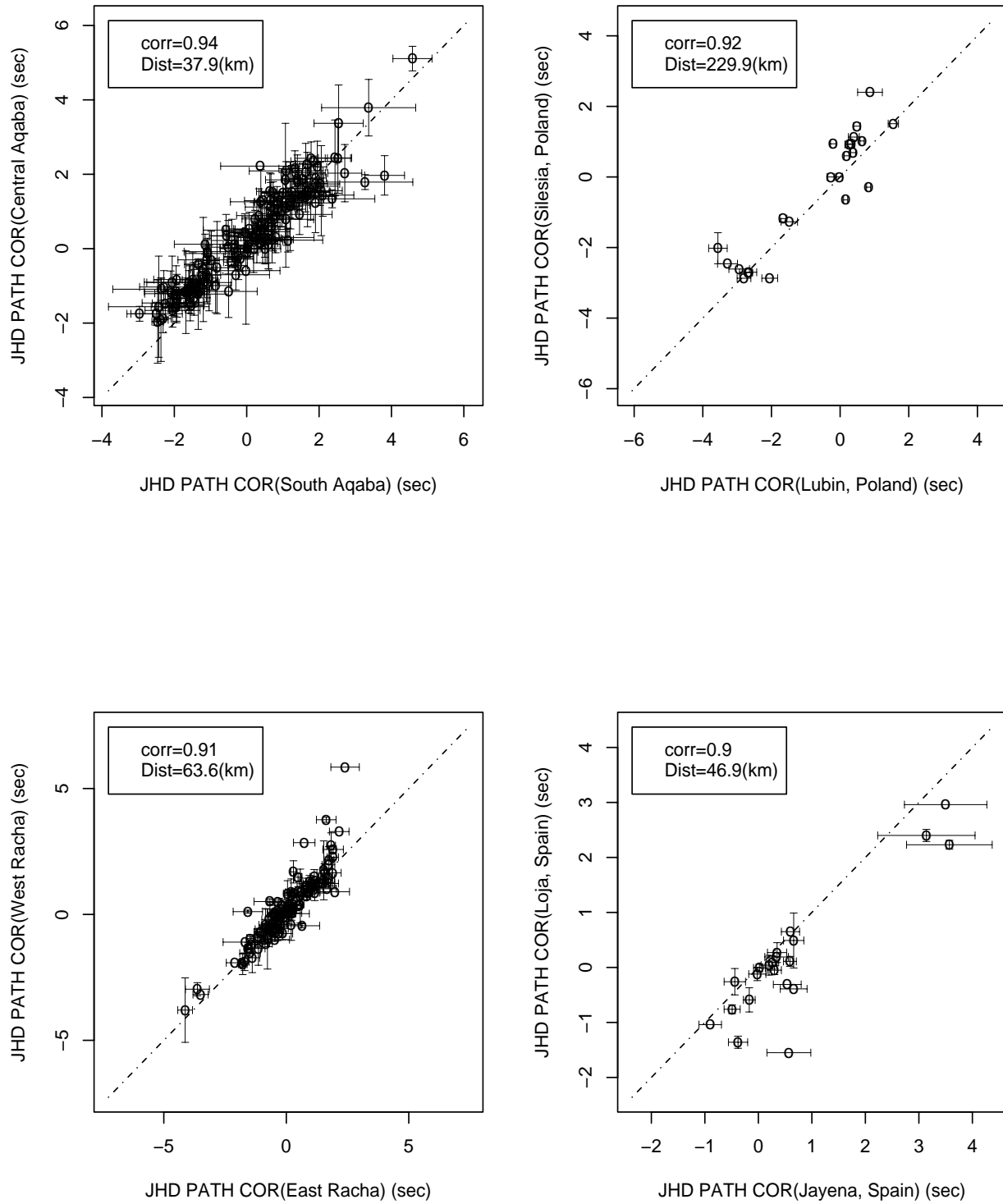
Figure 6. .Comparison of JHD corrections for some pairs of closely located clusters.

CORRELATION AMONG JHD CORRECTIONS – PAIRS OF CLUSTERS

DISTANCE BETWEEN CLUSTERS (degrees)

CORRELATION AMONG JHD CORRECTIONS – PAIRS OF STATIONS

DISTANCE BETWEEN STATIONS (degrees)
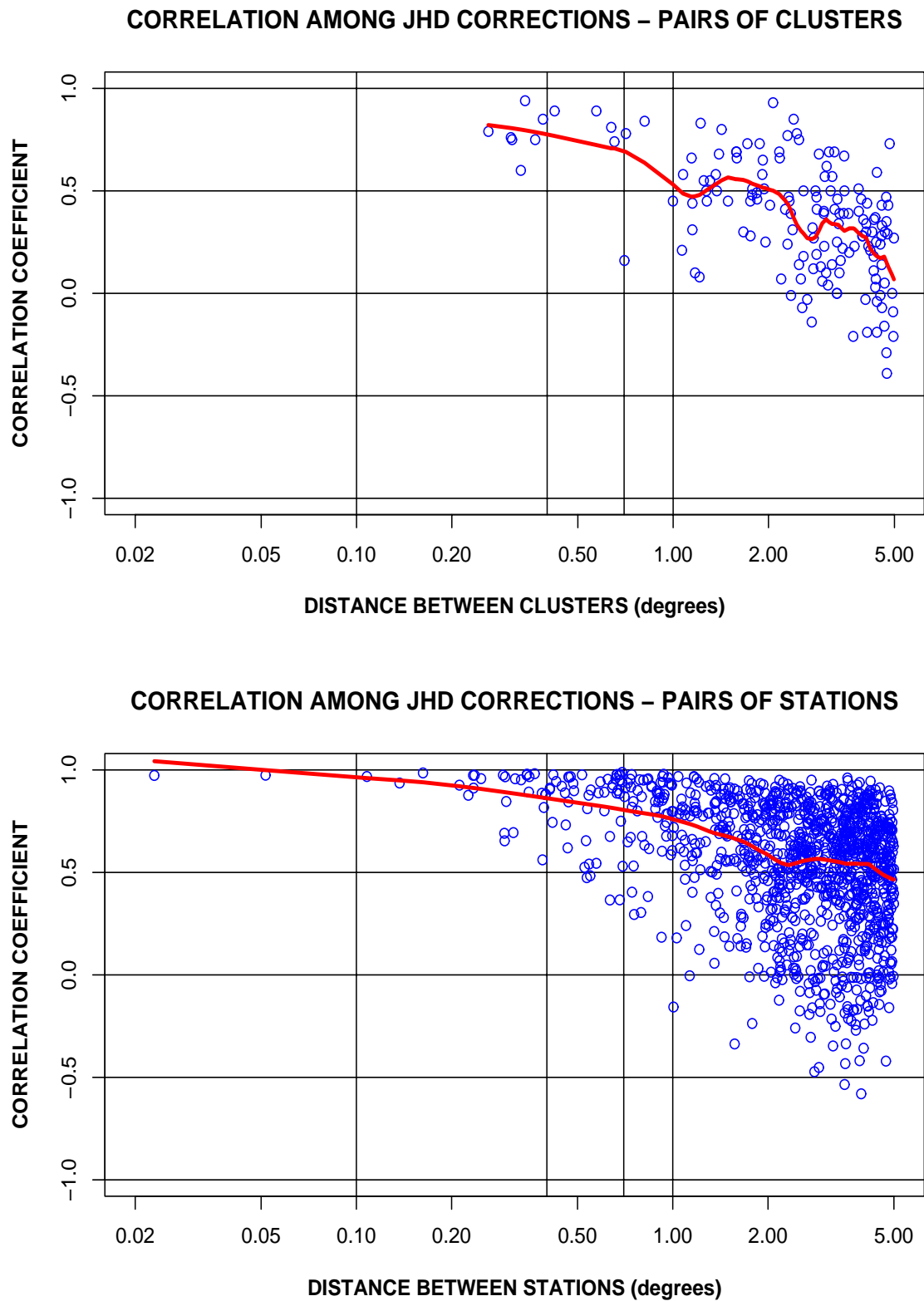
Figure 7. Correlation between JHD corrections as a function of distance among pairs of clusters with the same station (to the left) and among pairs of stations with the same clusters (to the right).
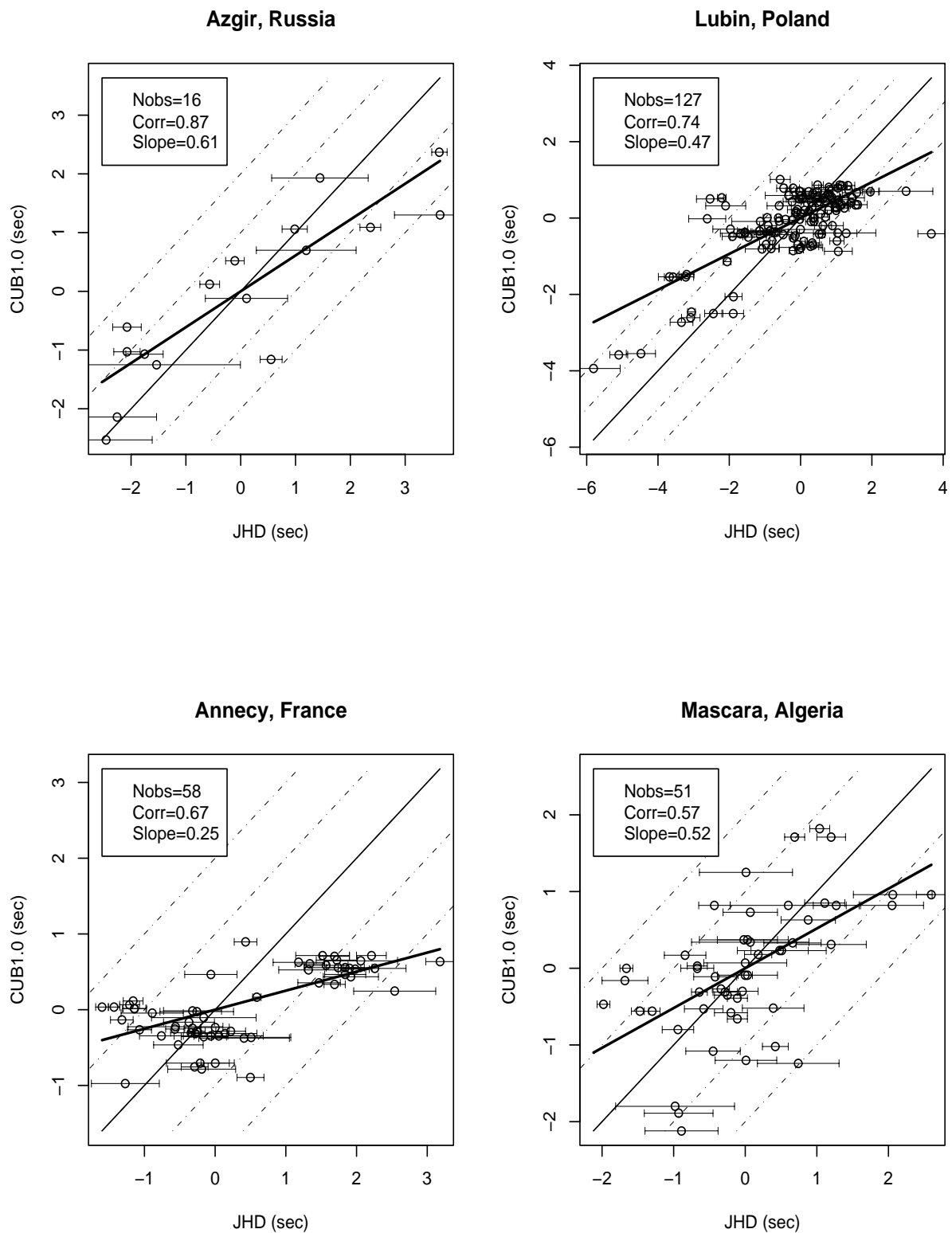
Figure 8. Comparison of JHD and CUB1.0 path corrections for four of the clusters. The error bars for JHD corrections indicate 90% confidence intervals.
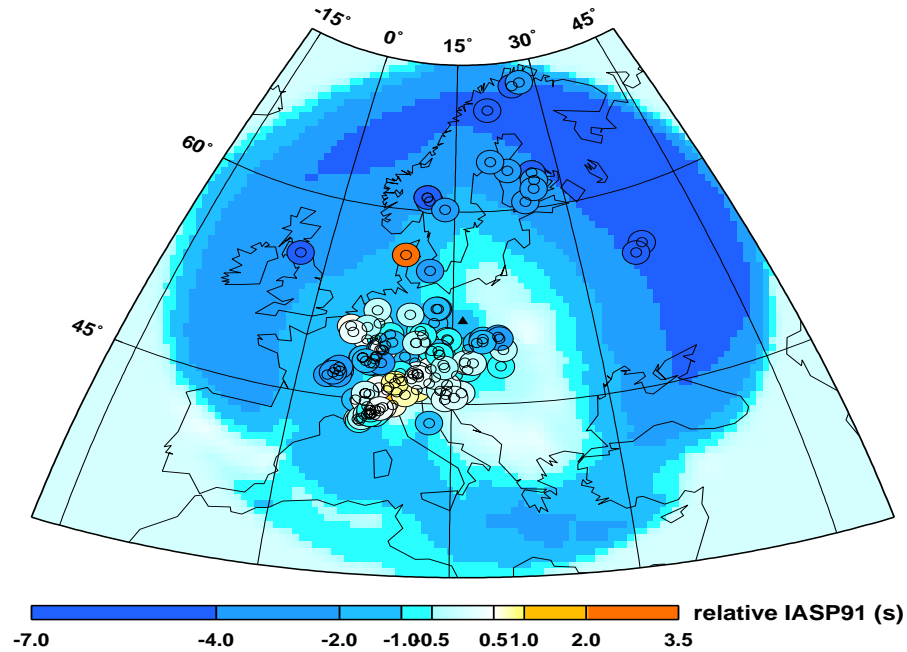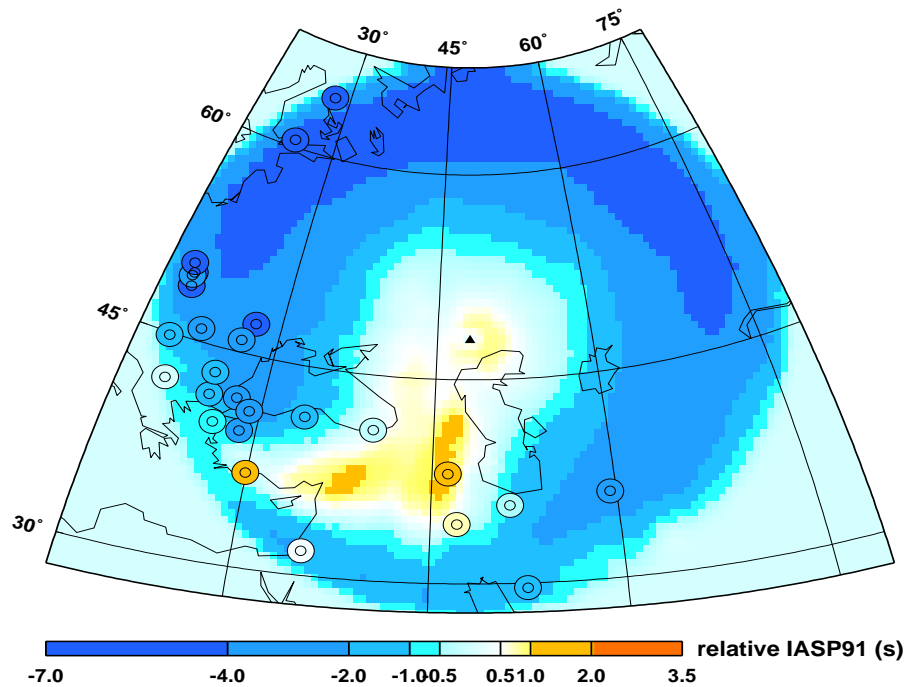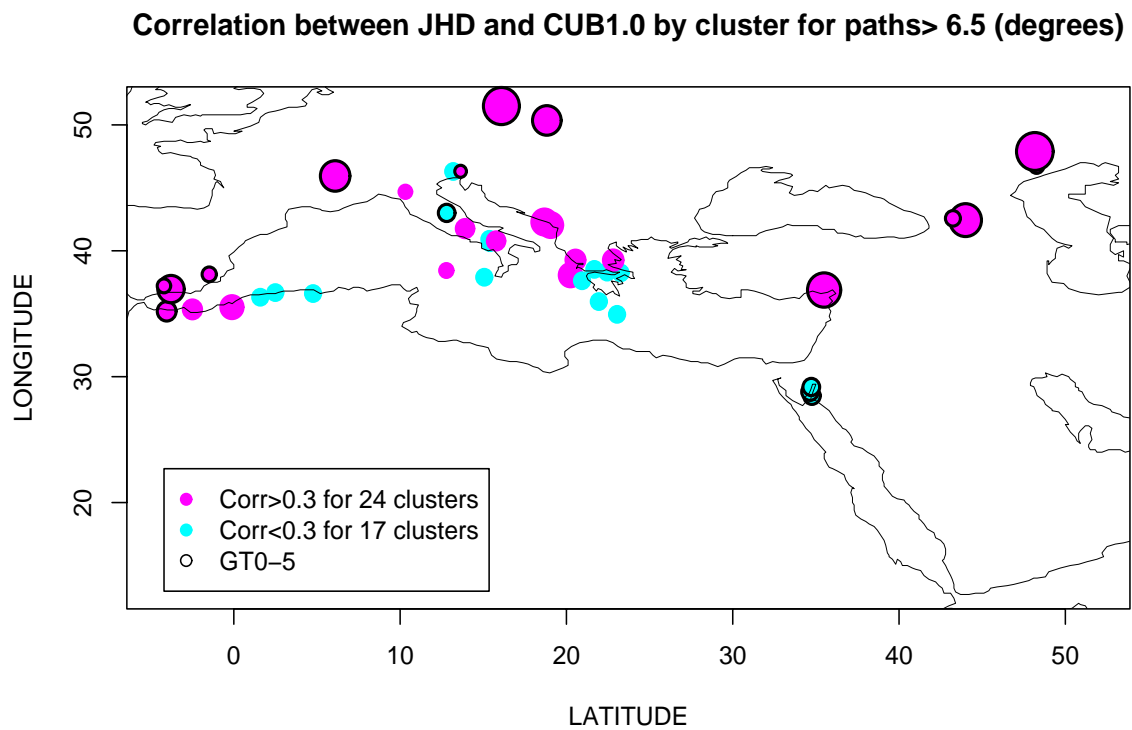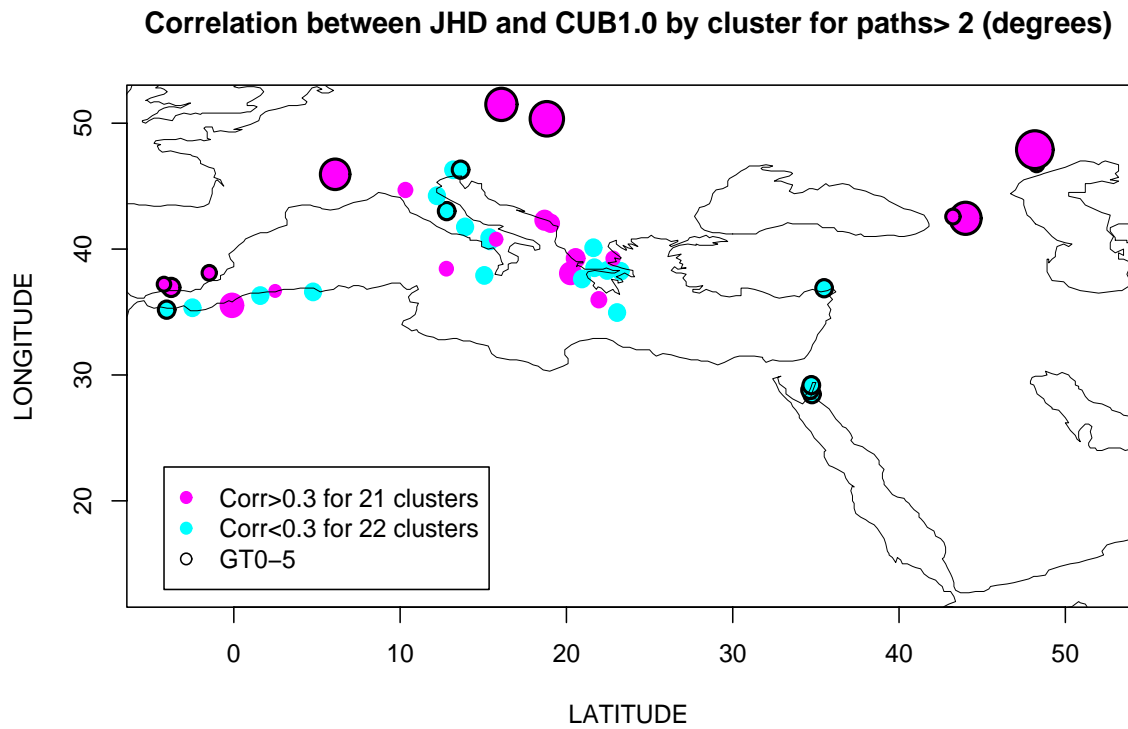
Figure 9. Comparison of JHD and CUB1.0 for the Azgir, Russia and Lubin, Poland clusters. The JHD corrections are plotted on top of the SSSC map derived for CUB1.0.
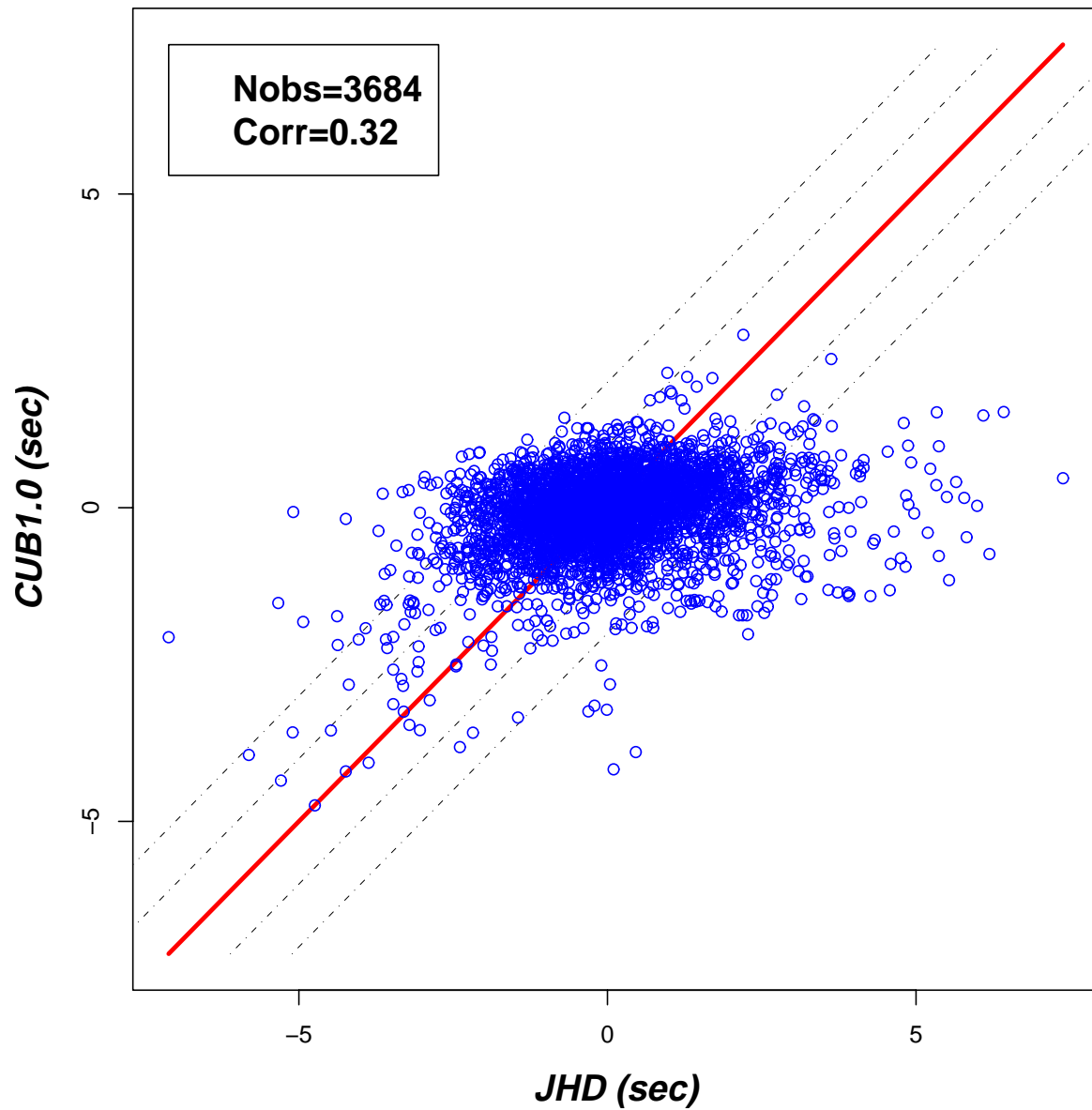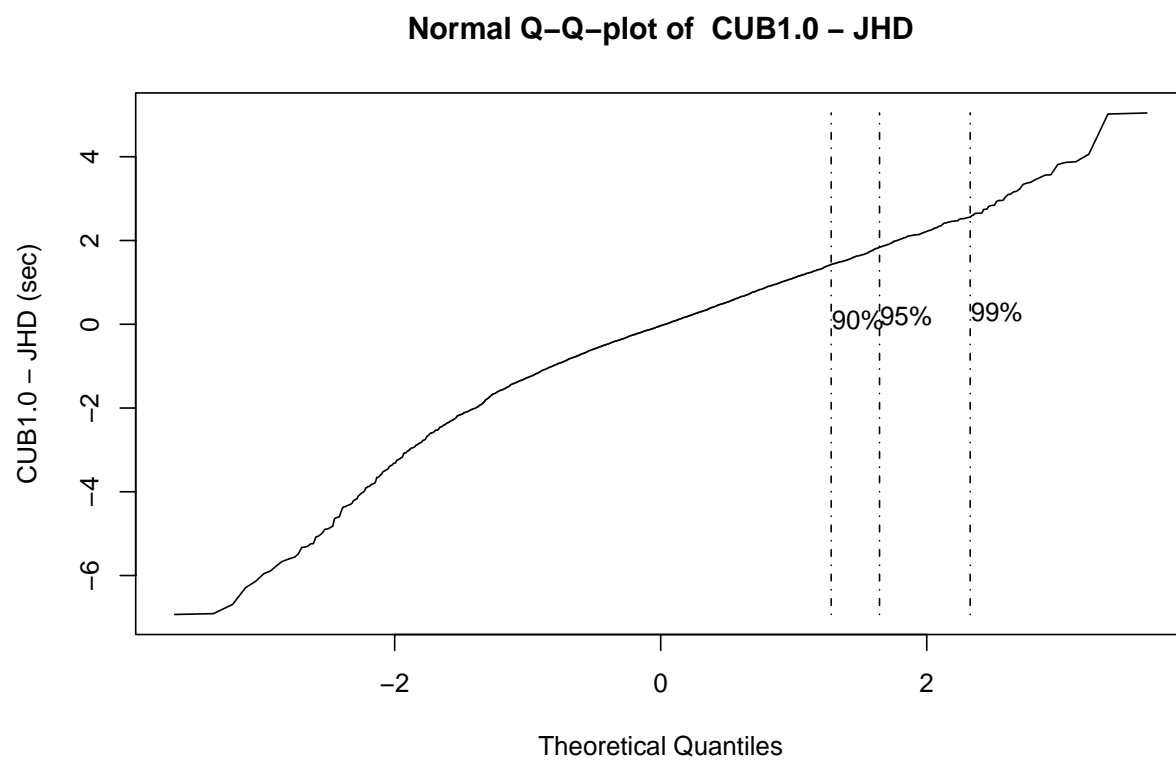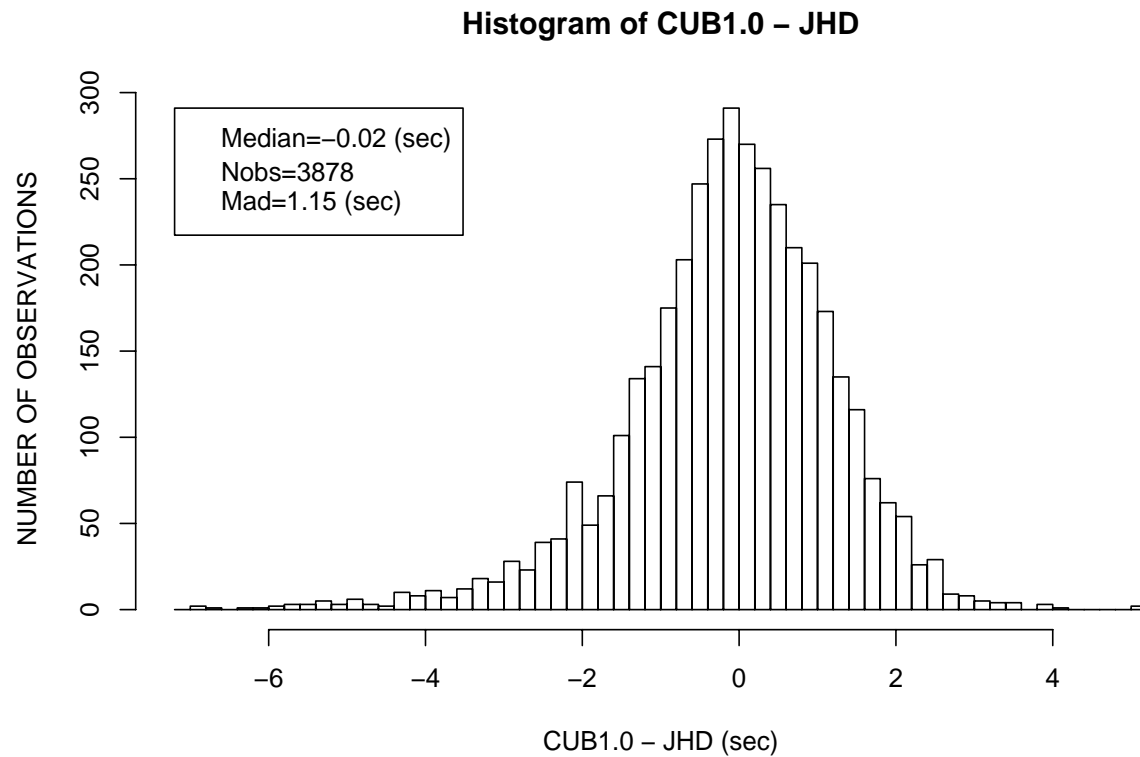
Figure 10. Comparison of all empircal (JHD) and model based (CUB1.0) path corrections of the event clusters.
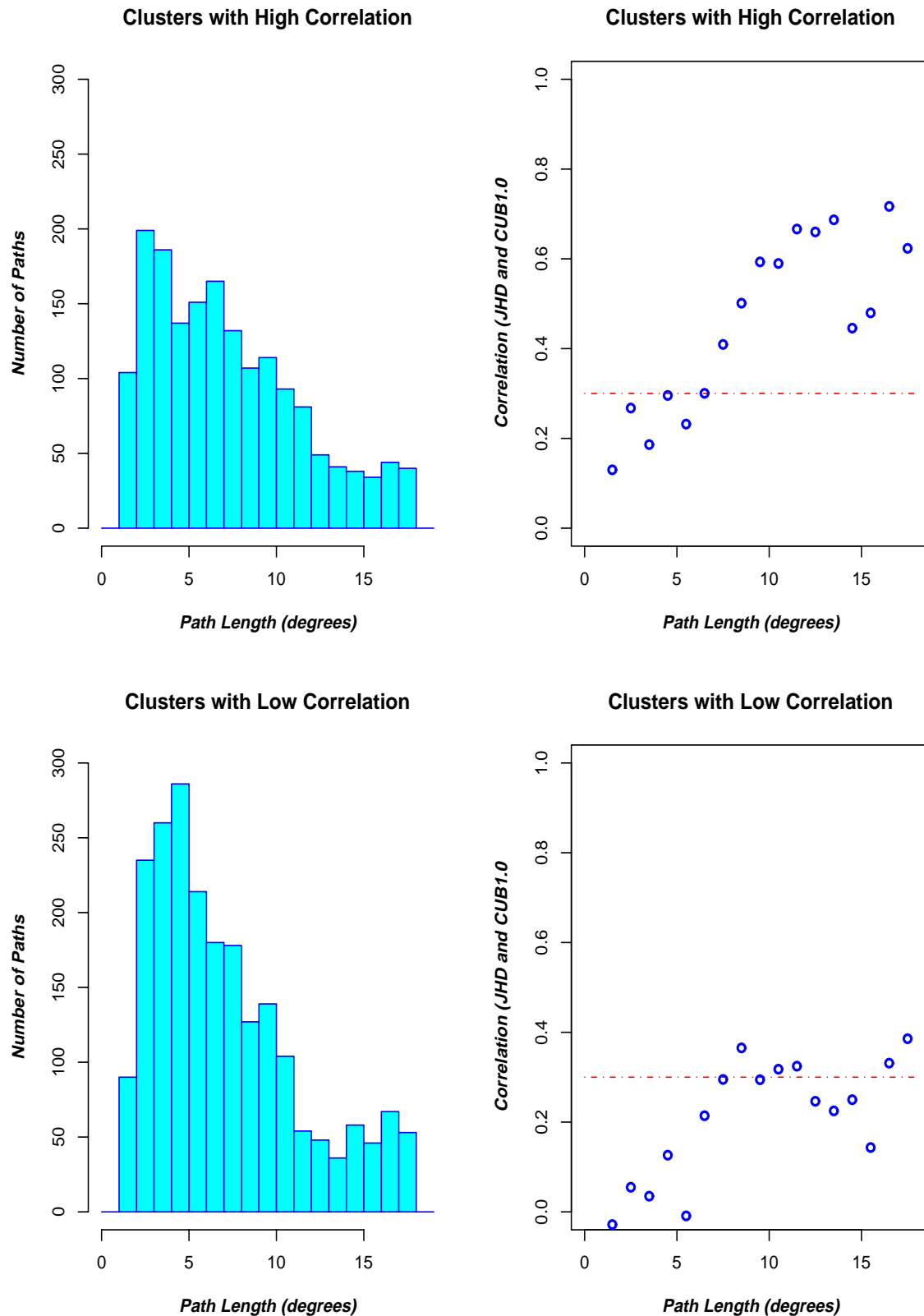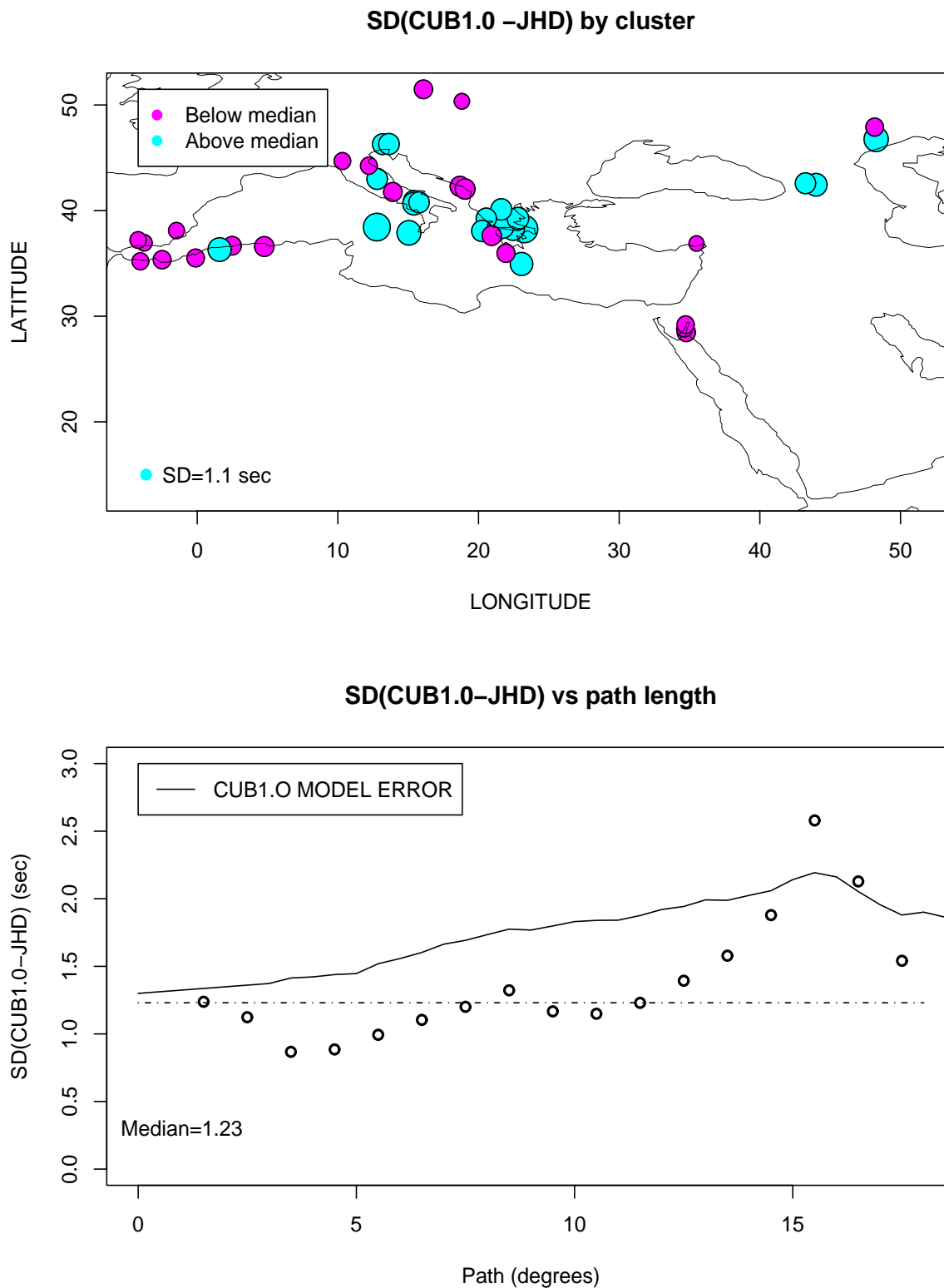
Figure 11. Correlation as a function of path length (degrees) for cluster with high correlation (top) and with low correlation (bottom). The histograms indicate the distribution of the paths lengths. The low correlation clusters have paths concentrated at shorter distances.

Correlation between JHD and CUB1.0 by cluster for paths> 2 (degrees)

Correlation between JHD and CUB1.0 by cluster for paths> 6.5 (degrees)

Figure 12. Correlation coefficients for the clusters plotted according to locations of the events. The upper maps includes all data, while paths shorter 6.5 degrees were omitted for the lower map.

Histogram of CUB1.0 − JHD

Median=−0.02 (sec)
Nobs=3878
Mad=1.15 (sec)

CUB1.0 − JHD (sec)

Normal Q−Q−plot of CUB1.0 − JHD

90% 95%   99%

Theoretical Quantiles

Figure 13. The distribution of theCUB1.0-JHD differences.

SD(CUB1.0 –JHD) by cluster

SD(CUB1.0–JHD) vs path length

Figure 14. The map above shows the distribution of standard deviation of the CUB1.0-JHD differences by cluster location. The lower diagram shows the standard deviation of the differences (circles) as a function of distance. The distance dependence of the a priori CUB1.0 model error is drawn for comparison.